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To: Dr. D. Mills
Director of Research

CORAUX - EXPERT SYSTEM FOR DIAGNOSIS OF STEAM PLANT CORROSION PROBLEMS IN STEAM TURBINE GENERATOR AND AUXILIARY EQUIPMENT

P. Mayer and D. LeFrancois

CORAUX expert system package was developed for use by electric utility and steam power plant personnel during investigation into the cause of steam turbine generator and steam plant auxiliary equipment corrosion damage. It is intended to assist their efforts to recognize and identify a basic cause of the damage under investigation. The program guides the user to the most likely damage mechanism by asking simple questions, answers to which can be obtained by determining the damage location, type of metal and from visual inspection of the damaged component.

For the first time, decades of accumulated knowledge, expertise and experience of the builders and operators of steam power plants are available in a microcomputer accessible form. In a matter of seconds one can diagnose a damage mechanism with confidence. CORAUX does not eliminate the need for a thorough metallurgical analysis during the failure investigation. CORAUX is based on reliable information published in the public domain and accepted by the practising experts in the area of steam power plant corrosion damage analysis.

The CORAUX expert system package is designed for ease of use, and no previous computer experience or computer programming knowledge is required.

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1. INTRODUCTION

A survey of about 500 utility turbines larger than 100 MW showed that corrosion failures occur in 4 to 5% of operating turbines each year. Considering that it takes an average of 4 years for corrosion to result in a failure, about 20% of operational large turbines are under attack at any given time. Eliminating steam turbine failures, as well as auxiliary component failures, could be worth billions each year to the electric power industry.

The aggressive service environment of steam power plants is largely the reason for these failures since the combined effects of stress, temperature, corrosion, erosion and vibration cause deterioration of material properties and in some cases reduction in wall thickness.

Determination of the corrosion damage mechanism is important for the prevention of future problems. The root cause for a failure can be established and proper ameliorative measures taken only when the damage mechanism is identified correctly. The correct identification of damage mechanisms is a complex process which may include many individuals and institutions. Technical specialists in metallurgy, chemistry, combustion, and power plant design frequently co-operate with the station staff in a failure investigation. These individuals rely on personal experience and a large amount of reports, theories, studies, private communications and investigations concerning the different failure modes and mechanisms.

As a result of many years of serious effort by the utilities and manufacturers to mitigate the problem of failures due to corrosion, information exists which make possible correct identification of all routine failure mechanisms which occur in currently operating systems. It is believed that proper dissemination of this knowledge and future findings will contribute to fewer incidents of failures. Expert systems, also known as knowledge-based systems, appear to be an effective tool for transferring this knowledge gained through research and field experience to individuals responsible for the design, construction, operation and maintenance of fossil-fired power generating stations. Expert systems are generally considered to be computer programs that use knowledge and inference procedures to solve problems instead of the traditional programs utilizing data and algorithms.

The CORAUX expert system package was developed for use by electric utility and power plant personnel during investigations into the cause of corrosion damage. It is intended to assist their efforts to recognize and identify a basic damage mechanism that can produce the type of damage under investigation. The program guides the user to the most likely damage mechanism by asking simple questions, answers to which can be obtained by determining the failure location, type of metal, and from visual inspection of the damaged component.

This report begins by discussing the primary corrosion damage mechanisms which occur in steam turbine generators and steam plant auxiliary equipment, then it moves on to describe expert systems in general which leads to a discussion of the CORAUX expert system package. Finally, an example of a diagnostic session with CORAUX is presented and concluding remarks are given.

2. CORROSION PROCESSES IN STEAM TURBINE GENERATORS AND STEAM PLANT AUXILIARY EQUIPMENT

Each component at a steam power plant possesses its unique corrosion problems due to: attack by service environment (high temperature, aggressive gasses and liquids, erosion, vibration, mechanical stresses, etc), human error, and incorrect and inconsistent application of ameliorative measures.

A steam power plant consists of three heat transport circuits: fuel-air, water-steam, and condenser cooling. In the fuel-air stream the fossil fuel is burned in air, transfers its heat to a series of heat exchangers, is cleaned of particulate matter, may be scrubbed of sulfur oxides, and exits through the stack. In the water-steam circuit, clean feedwater is converted into superheated steam in a boiler, which expands through a series of turbines, converting its heat into mechanical energy, and is condensed, conditioned, pumped, and heated as feedwater back into the boiler. In the condenser-cooling stream, cold water is passed through the condenser and can be recirculated if a cooling tower is used or is returned back to the source of the cooling water.

The equipment is usually divided into: boiler (steam generator) and auxiliaries. This paper is concerned only with corrosion which takes place in steam turbine generators and steam plant auxiliaries. All known mechanisms of routinely occurring corrosion have been summarized in TABLE 1. Each of these damage mechanisms is considered to be a primary way in which failure can occur. As well, secondary failures are always a concern after an initial failure.

3. EXPERT SYSTEMS

3.1 General Description

An expert system is a type of artificial intelligence program that emulates the interaction a user might have with a human expert on a subject area. Expert systems can be developed for any problem that involves a selection from among a definable group of choices where the decision is based on logical rules. The rules can involve relative probabilities of a choice being correct. Any area where there is a person or group of persons that have special expertise needed by others is a possible area for expert systems. Anything from identification of biological specimens, to automating complex regulations, to aiding customers in selecting from among a group of products, to automated user assistance is possible.

Expert systems deal with knowledge rather than data and the files they use are often referred to as knowledge bases. The rules that the program uses are IF-THEN type rules. A rule is made up of a list of IF conditions (normal English sentences) and a list of THEN conditions (more sentences) or statements about the probability of a particular choice being the appropriate solution to the problem. The computer determines what additional information it needs and how best to get this information. If possible, the program will derive information from other rules rather than

asking the user. This ability to derive information allows the program to combine many small pieces of knowledge to arrive at logical conclusions about complex problems.

The final goal of an expert system is to select the most appropriate solution to a problem based on the data input by the user. If more than one solution is possible the program could provide a list of the possible solutions arranged in order of probability.

3.2 Benefits and Risks

Expert systems offer the following benefits:

- The knowledge about a limited domain is captured in the detail required for machine logic processing; a good knowledge representation will identify areas where the knowledge is uncertain or incomplete; areas for further research become clearly defined and the experiments to be performed are readily apparent (sharpening the expert).

- Human experts can be distracted or rushed and led to incorrect or inconsistent deductions; the expert system will always apply the same logic and give consistent results; the results will be correct if the rules are: when the expert system cannot arrive at a conclusion, it refers the user to the human expert (best knowledge base always gives best conclusion).

- All conclusions reached by the expert system are justified by inspectable rules; the human expert is freed from remembering all the details of the justification; this is a great time saver in areas where justification is repeatedly requested for slightly different inputs; in cases of disagreement among experts, the knowledge base challenges other experts to point out errors or to generate a correct rulebase (public thinking tool).

- With appropriate help facilities, an expert system can become an excellent tutor for transferring knowledge from an expert to his successor; this provides a company with some measure of protection against loss of expertise through attrition (preservation of knowledge).

- Non-specialists have access to expert knowledge if the expert is not available; problems that are well understood can be solved by anyone who has excess to the expert system, this frees the expert from repeatedly executing the same task so that he can concentrate his efforts on acquiring new knowledge (efficient use of manpower).

The risks involved in expert systems are the same as those associated with any computer program. The conclusions arrived at by an expert system may be wrong if the rules are incorrectly written and/or when the data entered by the user is wrong. Although CORAUX is designed to guard against misinterpretation, conclusions should be treated like any conclusions of a single expert. A second opinion is recommended if an incorrect conclusion entails great risks.

3.3 The Expert System Shell Used

A program used to build an expert system is usually called an *expert system shell.* EXSYS[1], one of the many shells available, was used to create the expert system described in this paper. EXSYS is a generalized expert system development package. Expert systems can be developed with EXSYS for any problem that involves a selection from among a definable group of choices where the decision is based on logical rules. The rules can involve relative probabilities of a choice being correct.

Expert systems developed with EXSYS will ask the user questions relevant to a subject. The user answers by selecting one or more answers from a list by entering a numeric value. The computer will continue to ask questions until it has reached a conclusion. The conclusion may be the selection of a single solution or a list of possible solutions arranged in order of likelihood. The computer can explain, in English, how it arrived at its conclusion and why.

Expert system shells, such as EXSYS, coupled with the advance in micro-computer technology means that expert systems can be effectively built, installed on personal computers, and used by all who may need the assistance at low cost.

4. CORAUX - EXPERT SYSTEM PACKAGE - STEAM PLANT DIAGNOSIS OF CORROSION PROBLEMS IN STEAM TURBINE GENERATOR AND AUXILIARY EQUIPMENT

CORAUX expert system package was developed for use by electric utility and steam power plant personnel during investigation into the cause of steam turbine generator and steam plant auxiliary equipment corrosion damage. It is intended to assist their efforts to recognize and identify a basic cause of the damage under investigation.

The acceptance of an expert system depends on the credibility of its knowledge base. In the conceptual design of CORAUX, two criteria were established for selecting the main source for the factual portion of the knowledge base. The facts should have been: (i) published in public domain so that their reliability could be judged; and (ii) accepted by the practising experts in the area of corrosion damage analysis.

The "Corrosion in Fossil Fuel Power Plants" review Section in the ASM Metals Handbook[2] met both criteria and was chosen to be the factual framework for CORAUX.

The CORAUX knowledge base was constructed around the 19 basic corrosion damage mechanisms shown in TABLE 1. These damage mechanisms can independently or jointly bring a failure into being. The damage mechanisms can be determined, with a high degree of certainty, from location of the damage, type of metal used and characteristic appearance parameters. The relationships between corrosion damage mechanisms and these factors are well established with very little ambiguity. This knowledge is organized into a decision tree structure incorporating the facts from the ASM Metals Handbook and heuristic components contributed by the

developers of CORAUX. The facts are expressed in the form of production rules using the EXSYS expert system development package.

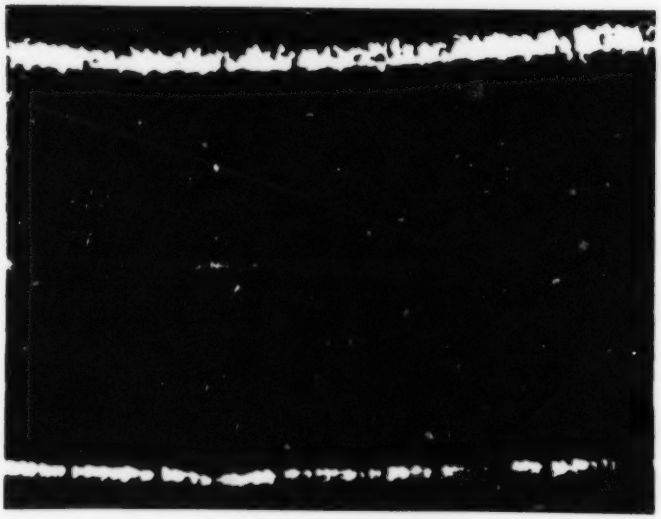
Expert systems developed with EXSYS, such as CORAUX, can be run on any IBM PC, XT, AT or compatible computer which has at least 256 K of RAM, one single sided disk drive, and uses DOS Version 2.0 or higher. An easy to follow User's Guide accompanies the software and gives more details regarding system requirements. The guide describes, and explains how to use, all the features of CORAUX (running, printing, displaying graphics, etc). The CORAUX User's Guide can also be used as a reference and/or learning tool since it includes descriptions of all the basic corrosion damage mechanisms used in the program. This User's Guide together with the floppy disks make up the CORAUX expert system package.

Even though CORAUX is a very helpful system it does not eliminate the need for a thorough metallurgical analysis during the failure investigation since such an analysis is essential in many cases to confirm or ascertain the responsible damage mechanisms.

By now the reader should be aware that corrosion damage which occur in boilers have been omitted from this system. This is certainly not because boiler failures due to corrosion are insignificant occurrences. Boiler tube failures continue to be the single largest source of forced outages in fossil fired electricity generating stations. It is for this reason an expert system, called COREXYS™, has been developed solely for diagnosis of boiler tube failures due to corrosion. The COREXYS™ expert system package comes complete with a User's Guide and disks, and is available upon request.

5. EXAMPLE OF A DIAGNOSTIC SESSION

For the purpose of demonstrating a diagnostic session with the CORAUX expert system, the tube failure in the following Figure was chosen.



This damage occurred in a copper alloy feedwater heater tube, and is characterized by horseshoe like pits, determined through a visual observation

First, the CORAUX expert system requests information on the damage location. The user is asked to choose from six specific locations shown in the first screen.

Screen No 1

The location of the corrosion damage is:

1. the condensers
2. the deaerators and feedwater heaters
3. the steam turbines
4. the generators
5. the flue gas handling system
6. the ash handling system

Enter number(s) of appropriate value(s), WHY for information on the rule being applied or <H> for help.

The user knows that the damage location is the feedwater heater and enters 2 and presses ENTER and 2 again on the next screen (No. 2) and ENTER.

Screen No 2

The location of the corrosion damage is:

1. the deaerator(s)
2. the feedwater heater(s)

Enter number(s) of appropriate value(s), WHY for information on the rule being applied or <H> for help.

Then the system requests more specific information on the location of the tube damage on the third screen.

Screen No 3

The corrosion damage is:

1. on the tubes
2. on another part of the component

Enter number(s) if appropriate value(s), WHY for information on the rule being applied or <H> for help.

The user knows that the damage occurred on the tube and enters 1 and presses ENTER.

The system automatically determines what to ask next in order to narrow down the likely damage mechanisms. In this case information regarding the metal type is required.

Screen No 4

The tubes are made of:

1. copper alloys
2. carbon or stainless steels

Enter number(s) of appropriate value(s), WHY for information on the rule being applied or <H> for help.

Since the tube is made of copper alloys, the user enters 1 and presses ENTER.

Screen No 5

Inspection of the corrosion damage indicates that

1. the component has failed by a thick-edged fracture
2. when dried, a thin continuous layer (copper colour) sheds from the tube
3. there is heavy scaling (leafy appearance, black in colour) taking place on the tube surface
4. the corrosion attack (deterioration) is uniformly distributed over the tube surface
5. there are deep circumferential grooves (condensate grooving) on the tubes
6. there are horseshoe like pits visible on the surface
7. none of the above features can be identified

Enter number(s) of appropriate value(s), WHY for information on the rule being applied or <H> for help.

Since 6 best describes the damage, 6 is entered as the selection for Screen 5.

Based on the provided information, the system performs a diagnosis and determines the feedwater heater tube damage mechanism. A detailed diagnosis is displayed. The user is then given the option of printing out this information. Finally, the explanation screen is displayed and a one-line summary of the diagnosis is presented.

By entering 1 at this point, the user can take a look at the rule which was applied for determining the damage mechanism (Erosion Corrosion in this case).

RULE NUMBER: 86
IF:

(1) The location of the corrosion damage is the deaerators and feedwater heaters

and (2) The location of the corrosion damage is the feedwater heater(s)

and (3) The corrosion damage is on the tubes

and (4) The tubes are made of copper alloys

and (5) Inspection of the corrosion damage indicates that there are horseshoe like pits visible on the surface

THEN:

The corrosion damage mechanism is EROSION CORROSION - Probability = 1

Input if line # for derivation, <K>-Known data, <C>-choices ↑ or ↓ previous or next rule, <J>-jump, <H>-Help or <ENTER> to continue:

6. SUMMARY

A rule-based system, to assist thermal power plant staff in recognizing and identifying basic causes of steam turbine generator and auxiliary equipment damage due to corrosion was developed. This microcomputer based software package is an essential tool for efficient analysis and resolution of equipment problems through correct determination of the failure mechanism which is necessary to establish root cause of the failure. The program allows consistent application of ameliorative measures to effectively mitigate routinely occurring equipment problems due to corrosion.

Recommended by:

R.G. Fleck
Supervising Engineer
Materials Technology Section
Metallurgical Research Department

Prepared by:

P. Mayer
Senior Metallurgist
Materials Technology Section
Metallurgical Research Department

Approved by:

J. Brown
Manager
Metallurgical Research Department

for P. Mayer

D. LeFrancois
Summer Student
Materials Technology Section
Metallurgical Research Department

7. REFERENCES

1. EXSYS is an Expert System Development Package, available from EXSYS Inc. P.O. Box 75158, Contr. 14 Albuquerque, NM 87194, USA.

2. Metals Handbook, p. 985-1008, Vol. 13, 1987 American Society for Metals (ASM).

TABLE 1

CORROSION PROCESSES WHICH OCCUR IN STEAM TURBINE GENERATORS AND AUXILIARY EQUIPMENT

CORROSION PROCESS	CONDENSERS	DEAERATORS	FEEDWATER HEATERS	STEAM TURBINES	GENERATORS	FLUE-GAS HANDLING SYSTEM	ASH HANDLING SYSTEM
	EQUIPMENT						
Scaling and plugging							•
Dew-point corrosion						•	
Oxidation				•			
SCC-low cycle fatigue				•			
Erosion				•		•	
Pitting			•	•		•	
Crevice corrosion and/or under deposit corrosion			•	•		•	
Exfoliation			•				
Snake skin formation			•				
Corrosion fatigue		•		•			
SCC		•	•	•	•	•	
Erosion corrosion	•	•	•	•			•
General corrosion		•	•			•	
Crevice corrosion and/or pitting	•						
Dealloying	•						
Sulfide attack	•						
Galvanic corrosion	•			•			
Condensate corrosion	•		•				
Environmental cracking	•						